A11102 129004

NAT'L INST OF STANDARDS & TECH R.I.C.

A11102129004

/Bureau of Standards journal of research
QC1 .U52 V6;1931 C.1 NBS-PUB-C 1928

THE TENSILE PROPERTIES OF ALLOY STEELS AT ELEVATED TEMPERATURES AS DETERMINED BY THE "SHORT-TIME" METHOD

By William Kahlbaum,[1] R. L. Dowdell, and W. A. Tucker

ABSTRACT

By means of "short-time" tension tests a series of alloy steels has been tested at different elevated temperatures. The proportional limit was determined in each case. The materials tested were a plain carbon steel and commercial alloys of chromium, vanadium, and iron with and without additions of tungsten, silicon, or aluminum; also chromium-tungsten, nickel-molybdenum and several austenitic steels with and without tungsten. Metallographic study revealed very little intercrystalline weakness and no marked or significant change in structure resulting from the high temperature tests. The addition of tungsten increases the "structural stability" of the austenitic alloys. Hardness was determined as a further indication of tempering which might have occurred during the heating. A comparison of "short-time" test and "flow test" for pearlitic and austenitic steel is included.

CONTENTS

		Page
I.	Introduction	199
II.	Previous investigations	200
III.	Test methods	201
	1. Short-time tension test	201
	2. Long-time tension test—"flow" test	202
IV.	Materials	202
V.	Results	205
	1. General	205
	2. Microstructure	207
VI.	Discussion	208
VII.	Summary	217
VIII.	Acknowledgments	218

I. INTRODUCTION

During the last few years numerous papers have been published on the so-called "short-time" tension test and on the "long-time" or "flow" test for determining the tensile properties of alloys at elevated temperatures. Perhaps the main reason for the extensive investigations along this line is the fact that many types of industrial installations, such as steam boilers, turbines, cracking stills, extrusion liners, etc., are being gradually forced to higher working temperatues and pressures.

At present, engineers, in general, favor the "flow" or "creep" test for evaluating materials which must withstand service conditions involving continued loading at high temperatures, since this test

[1] Research associate, The Midvale Co., Philadelphia, Pa.

duplicates to some extent service conditions. The tension specimen is maintained under constant load at some predetermined temperatures for a long period, often several hundred hours. From the data thus obtained, the stress required to produce a definite extension, for example, 0.1 or 1.0 per cent in 1,000 hours at any given temperature can be calculated. On the other hand, a period of only three or four hours is required for carrying out the "short-time" tension test at high temperatures. The most essential part of this test is the determination of the stress, for any given temperature, at which the material ceases to behave elastically.

The information available on the correlation of results from short-time and from flow tests is rather limited. No conclusions that short-time tests can entirely replace flow tests are warranted on the basis of available information. It is believed, however, that a large amount of valuable preliminary information can be obtained with the short-time method with a great saving of time in the study and development of alloys for continuous service at elevated temperatures. In fact, since the advent of austenitic alloys for service at elevated temperatures there is still more reason for extended flow tests, such tests to be made for even longer periods of time than heretofore. As many austenitic alloys are metastable yet sluggish in their response to thermal treatment at temperatures in the vicinity of 1,200° to 1,300° F. (600° to 700° C.) it would not seem advisable to determine their characteristics by the short-time method only.

The group of materials reported upon in this paper includes both commercial alloy steels and some special alloys which had been made primarily to show the effects on the tensile properties of various alloying elements, such as silicon, chromium, nickel, vanadium, tungsten, molybdenum, and aluminum.

From a previous investigation [2] results were available on the characteristics, as determined by the flow test, of three of the alloys used in the present work. These have been included in the present report, and form the basis of a comparison of the properties of identical materials as determined by the two methods. Two of the alloys were austenitic in structure, whereas the other was representative of the martensitic class of this group of alloy steels.

All of the work reported here was carried out in accordance with the research associate plan [3] in cooperation with The Midvale Co., Philadelphia, Pa., except the tests with the plain carbon steel. This work was done by E. L. Jones, guest worker for The International Combustion Engineering Corporation, New York, N. Y.

II. PREVIOUS INVESTIGATIONS

A very extensive bibliography on the effect of temperature on the properties of metals has been published.[4] No attempt will be made in this report to give a detailed résumé of the previous work along

[2] H. J. French, William Kahlbaum, and A. A. Peterson, Flow Characteristics of Special Fe-Ni-Cr alloys and some Steels at Elevated Temperatures, B. S. Jour. Research, 5, (RP192) p. 125; 1930.

[3] Bureau of Standards Circular No. 296.

[4] Bibliography on Effect of Temperature on the Properties of Metals. (Published in 1928 by the A. S. M. E., 29 West Thirty-ninth Street, New York N. Y. This is now being brought up to date.) Compiled by the Joint Research Committee of A. S. M. E. and A. S. T. M. on the Effect of Temperature on the Properties of Metals.

this line. Some investigators [5] [6] [7] [8] [9] [10] have given some results from short time tension tests and of flow tests of the same materials. In a previous bureau report [11] the results of other investigators were given which showed that there were marked differences in the flow characteristics of similar steels reported by different laboratories. These differences depended on both the individual set-ups and on the interpretation of the data.

McVetty and Mochel [12] have emphasized the extreme care which must be used with the short-time method if the results are to be of value as well as the necessary refinements in the design of furnace, control of temperature, measurement of extension, and measurement of stress. Within the last few years, an optical extensometer having an accuracy of measurement of approximately 0.000004 inch has become available. With such an instrument, it has been found that the apparent values of the proportional limit of metals are considerably less than those obtained with dial types, by means of which the extension can be read only to about 0.0002 inch. According to McVetty and Mochel:

> A change in the accuracy of measurement of total elongation from 0.0002 inch to 0.000004 inch reduces the apparent value of proportional limit by about 17 per cent in the case of medium carbon steel and over 50 per cent in the case of the stainless iron.

The present tendency in both the short-time and flow tests of metals is toward higher sensitivity. The importance of extreme precautions of this kind has been further emphasized by McVetty.[13]

III. TEST METHODS

1. SHORT-TIME TENSION TEST

The method used for the short-time tension tests has been previously described and illustrated.[14] All of the tests were made with a hydraulic machine, and the elongations were measured by means of a Martens' extensometer with its optical lever system as modified by Tuckerman [15] and as described in Letter Circular No. 238, issued by the Bureau of Standards.

The thermocouple used for measuring the temperature of the test bar was mounted in the fillet of the standard 0.505-inch diameter bar. Before attempting to obtain any of the data for the stress-strain curve, the furnace was held at the desired temperature, by manual control,

---

[5] J. H. S. Dickenson, Some Experiments on the Flow of Steels at a Low Red Heat with a Note on the Scaling of Heated Steels, J. Iron & Steel Inst., **106**, p. 103; 1922.

[6] H. J. French and W. A. Tucker, Flow in a Low-Carbon Steel at Various Temperatures, B. S. Tech. Paper No. 296, p. 630; 1925.

[7] T. D. Lynch, N. L. Mochel, P. G. McVetty, The Tensile Properties of Metals at High Temperatures, Proc. Am. Soc. Testing Materials, **25**, pt. 2, p. 5; 1925.

[8] H. J. French, Methods of Test in Relation to Flow in Steels at Various Temperatures, Proc. Am. Soc. Testing Materials, **26**, pt. 2, p. 7; 1926; also Eng. News Record, **97**, p. 22.

[9] A. Pomp and A. Dahmen, Entwicklung einer abgekurtzen plufverfahrens zur entmittlung der dauerstandfestigkeit von stahl bei erhohten temperaturen, Mitteil. a. d. Kaiser-Wilhelm Inst. f. Eisenforschung, Dusseldorf, **9**, No. 3, 1927; also Stahl u. Eisen, **47**, p. 414; 1927.

[10] L. W. Spring, J. J. Kanter, "Long-Time" or "Flow" Tests of Carbon Steels at Various Temperatures with Particular Reference to Stresses below the Proportional Limit, Valve World, p. 260, August, 1928; also in a shorter form in Proc. Am. Soc. Testing Material **28**, pt. 2, pp. 80–116; 1928.

[11] H. J. French, H. C. Cross, and A. A. Peterson, Creep in Five Steels at Different Temperatures, B. S. Tech. Paper No. 362; 1928.

[12] P. G. McVetty and N. L. Mochel, The Tensile Properties of Stainless Iron and Other Alloys at Elevated Temperatures, Trans. Am. Soc. Steel Treat., **11**, pp. 73–100; 1927.

[13] P. G. McVetty, Testing of Materials at Elevated Temperatures, Proc. Am. Soc. Testing Materials, **28**, pt. 2, p. 60; 1928.

[14] See footnotes 8 and 11.

[15] Engineer physicist, Bureau of Standards.

for a period of two hours. The temperature variation from the center to the extremities of the gage length of the specimen was approximately 13° F. (7° C.) It was possible to run only one short-time test a day owing to the necessity of exercising extreme care in setting up and adjusting the extensometer. The actual duration of the average test was about one-half hour. The accuracy of the extensometer was 0.000004 inch per inch of extension while the load measurements were accurate to within one-half of 1 per cent.

2. "LONG-TIME" TENSION TEST—"FLOW" TEST

The equipment used in carrying out the flow tests has been previously described.[16, 17] The load was applied by weights at the ends of levers. The diameter of the test bar was 0.250 inch and the gage length, 2 inches. A shallow groove was cut close to the fillet at each end of the specimen, in which was secured a ring of platinum wire (32 B. & S. gage) used as a reference mark in measuring the extension of the bar. A cathetometer whose smallest direct reading was 0.00039 inch was used to measure the distance between reference marks at periodic intervals. The extension was calculated in inches per inch of gage length.

The automatic temperature controllers on the furnaces were actuated by means of thermocouples located close to the furnace windings, the temperature was maintained within a range of ±10° F. (±5.5° C.).

The duration of the flow tests was from 300 to 400 hours, and from the results were calculated the limits of stress producing a total extension or "flow" of both 0.1 per cent and 1 per cent in 1,000 hours.

IV. MATERIALS

A wide variety of ferrous alloys was tested. The chemical composition and treatment of these alloys are given in Table 1. The plain carbon steel (0.45 per cent carbon) listed is typical of material widely used for boiler drums in steam power plants. The remainder of the alloys were made, treated, and analyzed by The Midvale Co. with the exception of the two foreign alloys, FS–1 and FS–2. The list of alloys covers a rather wide range of composition, and they were made up primarily to show the effects of various alloying elements on the tensile properties at elevated temperatures as measured by the short-time method. All of the alloys were in the wrought condition, either forged or rolled, after which operation many had been heat-treated as shown in Table 1.

---

[16] See footnote 6, p. 201.

[17] See footnote 11, p. 201.

TABLE 1.—*Composition and condition of tested materials*

Designation	Chemical composition												Condition and treatment of material
	C	Mn	P	S	Si	Cr	Ni	V	W	Mo	Al	Fe	
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*		
4	0.45	0.55	0.025	0.040	0.22							Balance	Boiler drum forging; as forged.
10–518, lot A	.40	.57	.035	.040	.25	2.26		0.20				do	Treated in order to obtain yield point of 50,000 lbs./in.[2] Material hot rolled. 1,575° F., 1 hr., slow cool; 1,375° F., 1 hr., furnace cool.
10–518, lot B	.40	.57	.035	.040	.25	2.26		.20				do	Treated in order to obtain yield point of 80,000 lbs./in.[2] Material hot rolled. 1,575° F., 1 hr., air cool; 1,300° F., 1 hr., furnace cool.
EE1455	.55	.36			.16	2.07			1.48			do	Induction furnace heat 3 inch square ingot rolled to ¾ inch round. Annealed 1,400° F., 1 hr., furnace cooled. Oversize test bars then annealed 1,600° F., 1 hr., furnace cooled; 1,300° F., 1 hr., furnace cooled. Bars finished to size.
EE1456	.55	.41			1.26	2.10		.29	1.61			do	Same as EE1455.
EE1454	.53	.46			.24	2.05		.26	1.54		1.75	do	Do.
E3226, lot A	.36	.62	.026	.019	.19	2.47	0.14	.23	2.00			do	1,625° F., 8 hrs., cooled slowly to black heat; 1,350° F., 8 hrs., cooled 30° F. per hour to 1,100° F.; soaked, slow cooled 1,650° F., 7 hrs. oil; 1,050° F., 8 hrs., slow; 1,090° F., 8 hrs., slow; bars machined from large block after treatment.
E3226, lot B	.36	.62	.026	.019	.19	2.47	.14	.23	2.00			do	1,625° F., 8 hrs., air; 1,350° F., 8 hrs., cooled 30° F. per hour to 1,100° F.; soaked slow cool 1,650° F., 6 hrs., oil; 1,050° F., 7 hrs., slow; 1,160° F., 7 hrs., slow. Bars machined from large block after treatment.
HF1/45, lot A	.44	.48	.024	.017	.23	7.35			7.94			do	1,200° F., slow cooled; 1,300° F., slow cooled, machined; 2,250° F., 15 min., water; 1,200° F., 4 hrs., slow cooled.
HF1/45, lot B	.44	.48	.024	.017	.23	7.35			7.94			do	1,200° F., slow cooled; 1,300° F., slow cooled, machined; 1,875° F., 2 hrs., air; 1,200° F., 4 hrs., slow.
8/1317, lot A	.32	.70	.032	.031	.19	.62	2.35			0.31		do	1,560° F., 45 min., oil; 1,150° F., 1 hr., air.
8/1317, lot B	.32	.70	.032	.031	.19	.62	2.35			.31		do	1,560° F., 45 min., air; 1,150° F., 45 min., air.
E2457	.37	.39			1.50	10.5	1.61				1.50	do	Rolled bars, 1,600° F., 30 min., air; 1,200° F., 30 min., air.
7990	.53	1.58			.96	14.80	26.00		2.93			do	1,835° F., 1½ hrs., water.
FS–2, lot A:													
Creep test bars	.32	1.52	.028	.038	.03	12.93	34.90		Trace.			do	As rolled.
Short-time bars	.29	1.10	.028	.034	.03	10.20	34.50		Trace.				

TABLE 1.—*Composition and condition of tested materials*—Continued.

Designation	Chemical composition												Condition and treatment of material
	C	Mn	P	S	Si	Cr	Ni	V	W	Mo	Al	Fe	
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*		
FS-2, lot B:													
Creep test bars	0.28	1.45	0.032	0.027	0.03	11.12	35.90	-------	0.34	-------	-------	Balance	Rolled, annealed 1,650° F.
Short-time bars	.40	1.16	.027	.043	.05	10.24	34.80	-------	Trace.	-------	-------		
FS-1, lot A:													
Creep test bars	.19	1.62	.028	.027	.10	10.28	57.60	-------	3.19	-------	-------	do	As rolled.
Short-time bars	.22	1.74	.037	.030	.09	10.61	57.80	-------	3.47	-------	-------		
FS-1, lot B:													
Creep test bars	.20	1.66	.026	.029	.08	10.34	57.40	-------	3.30	-------	-------	do	Rolled, annealed 1,650° F.
Short-time bars	.21	1.73	.037	.036	.09	10.70	57.60	-------	3.33	-------	-------		

V. RESULTS

1. GENERAL

The tensile properties of all of the materials as determined by the short-time testing method are given in Table 2. Stress-strain curves for a number of representative alloys of different composition are given in Figures 1 to 11, inclusive. Figure 12 shows a comparison of the results of those alloys for which both proportional limits from the short-time tension tests and the flow characteristics were available.

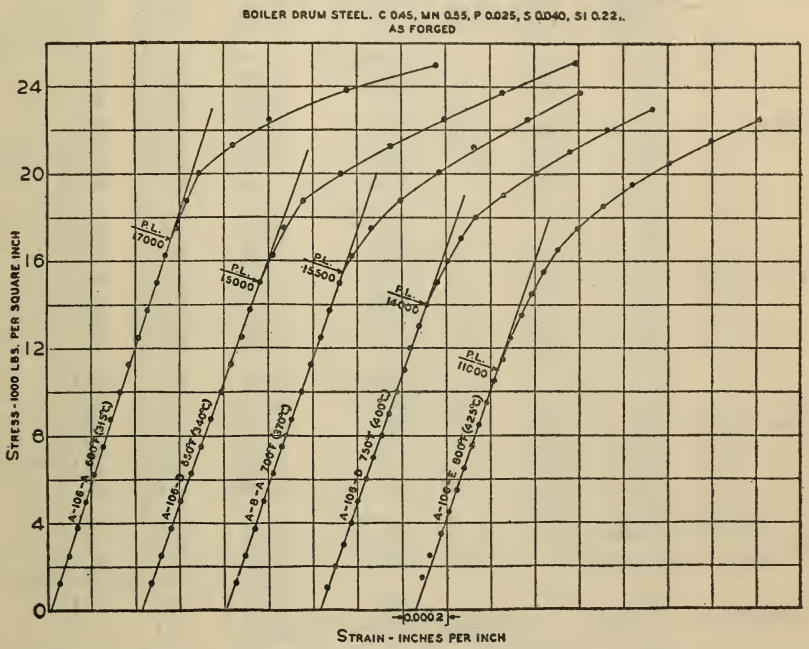

FIGURE 1.—*Stress-strain curves of medium carbon steel (boilerdrum) tested in tension at different temperatures*

TABLE 2.—*Tensile properties of materials tested in Table 1 at different temperatures*

Designation	Specimen No.	Test temperature	Proportional limit	Tensile strength	Elongation in 2 inches	Reduction of area	Brinell hardness No.
		° F.	*Lbs./in.*[2]	*Lbs./in.*[2]	*Per cent*	*Per cent*	
4 (1)	A-4-A	600	16,500	78,700	22.0	24.8	
	A-4-B	650	15,500	75,850	21.5	38.9	
	A-4-C	700	16,500	74,000	24.0	44.5	
	A-4-D	750	15,000	68,500	23.5	51.7	
	A-4-E	800	12,000	62,250	23.0	50.8	
4 (2)	A-106-A	600	17,000	80,000	27.0	38.1	
	A-106-B	650	15,000	77,500	26.0	42.7	
	A-8-A	700	15,500	71,500	22.0	48.8	
	A-106-D	750	14,000	66,000	26.5	53.0	
	A-106-E	800	11,000	67,000	24.0	49.1	
10-518, lot A	T-19	70	32,500	84,250	33.0	68.2	170
	T-15	70	30,000	82,250	31.0	70.8	
	T-3136	550	24,000	80,500	22.5	66.8	
	T-3127	550	22,500	75,000	27.0	69.8	
	T-125	800	18,500	73,750	26.5	68.8	
	T-3139	800	17,750	73,750	25.0	67.7	
	T-3113	1,000	6,000	39,000	36.5	88.3	
	T-11	1,000	4,400	40,000	37.5	85.1	
	T-121	1,200	500	26,750	41.0	92.8	

[1] Specimens of the first group of steel No. 4 were transverse test specimens.
[2] Specimens of the second group of steel No. 4 were longitudinal test specimens.

TABLE 2.—*Tensile properties of materials tested in Table 1 at different temperatures*—Continued

Designation	Specimen No.	Test temperature	Proportional limit	Tensile strength	Elongation in 2 inches	Reduction of area	Brinell hardness No.
		° F.	*Lbs./in.*[2]	*Llbs./in.*[2]	*Per cent*	*Per cent*	
10–518, lot B	T–261	70	63, 500	100, 650	27. 0	66. 1	201
	T–3109	70	58, 500	102, 500	27. 5	66. 8	
	T–3104	550	40, 000	91, 500	21. 0	68. 2	
	T–253	800	21, 500	83, 750	24. 0	68. 6	
	T–276	1, 000	8, 750	61, 500	27. 5	80. 4	
	T–257	1, 000	8, 375	51, 000	30. 0	87. 5	
	T–290	1, 200	600	37, 250	32. 0	91. 6	
EE1455		70	66, 000 E. L.[3]	111, 500	21. 2	52. 2	197
	1	850	25, 000	90, 000	23. 5	62. 7	
	4	850	25, 000	88, 500	24. 0	62. 2	
	5	950	16, 500	79, 500	25. 0	66. 5	
	6	950	18, 000	80, 000	25. 0	66. 5	
	3	1, 050	9, 800	63, 000	31. 5	79. 6	
	2	1. 050	10, 500	62, 500	30. 0	79. 2	
	7	1, 200	2, 000	52, 000	25. 0	78. 5	
	8	1, 200	4, 000	47, 500	27. 5	83. 2	
EE1456		70	75, 000 E. L.[3]	122, 000	21. 2	53. 1	219
	2	850	28, 000	99, 000	25. 0	63. 0	
	1	850	50, 000	92, 300	24. 5	59. 3	
	3	950	24, 000	85, 000	28. 0	71. 3	
	6	950	24, 000	81, 500	30, 0	73. 7	
	4	1, 050	18, 000	65, 000	32. 0	82. 2	
	5	1, 050	16, 000	63, 000	31. 5	80. 1	
	7	1, 200	8, 000	[4] 44, 000	33. 5	85. 8	
	8	1, 200	8, 000	53, 000	29. 0	86. 3	
EE1454		70	66, 000 E. L.[3]	104, 500	17. 7	34. 4	217
	1	850	29, 000	89, 000	21. 5	54. 0	
	2	850	30, 000	89, 500	21. 5	54. 3	
	5	950	24, 000	82, 200	22. 5	59. 6	
	3	950	22, 000	78, 500	23. 5	62. 7	
	6	1, 050	13, 000	68, 000	28. 0	74. 1	
	7	1, 200	8, 500	50, 500	32. 5	83. 7	
	8	1, 200	9, 000	48, 000	33. 0	84. 9	
E3226 Lot A		70	152, 000 E. L.[3]	201, 000	15. 0	52. 8	
	S–3504–1	1, 000	32, 500	113, 500	15. 0	56. 4	
E3226 Lot B		70	96, 000 E. L.[3]	132, 000	17. 0	52. 0	
	S–3504–2	1, 000	28, 000	84, 000	22. 0	73. 4	
HF1/45, lot A		70	75, 800	227, 800	8. 0	17. 5	
	F–1/45–3	1, 000	44, 000	163, 400	6. 0	11. 4	
	F–1/45–4	1, 000	46, 300	159, 400	6. 5	11. 4	
HF1/45, lot B		70	70, 000 E. L.[3]	153, 000	12. 0	36. 9	
	F–1/45–1	1, 000	21, 000	95, 000	15. 0	49. 1	
	F–1/45–2	1, 150	13, 500	73, 000	21. 5	66. 5	
8/1317, lot A		70	126, 000 E. L.[3]	156, 000	17. 0	59. 4	325
	1A	800	52, 500	123, 000	16. 5	61. 1	
	1E	800	52, 500	132, 000	15. 0	57. 5	
	1C	900	35, 000	109, 500	17. 5	69. 7	
	1D	900	34, 000	111, 500	17. 0	68. 3	
	1F	1, 000	12, 000	98, 000	20. 0	75. 6	
8/1317, lot B		70	96, 000 E. L.[3]	135, 500	17. 6	54. 9	281
	2C	800	42, 000	110, 500	16. 5	57. 5	
	2F	800	39, 000	113, 000	16. 0	55. 6	
	2A	900	32, 000	101, 000	17. 0	61. 5	
	2B	900	30, 000	101, 000	16. 5	63. 5	
	2D	1, 000	9, 000	86, 250	17. 5	70. 7	
	2E	1, 000	9, 000	87, 000	18. 0	72. 0	
E2457		70	108, 000 E. L.[3]	135, 500	17. 0	40. 7	258
		70	109, 500 E. L.[3]	140, 000	17. 2	38. 5	262
	B2	700	42, 500	122, 500	16. 0	35. 0	
	B3	950	30, 000	106, 500	19. 0	54. 1	
	B7	950	22, 000	107, 000	20. 0	52. 5	
	B8	1, 015	13, 000	79, 250	25. 0	66. 8	
	B6	1, 075	4, 700	64, 000	29. 0	74. 1	
	B5	1, 200	2, 250	41, 250	32. 5	84. 5	
	B9	1, 200	2, 000	38, 250	35. 0	85. 9	

[3] Elastic limit determined by The Midvale Co.
[4] Tensile specimen was piped which resulted in a low tensile strength value.

TABLE 2.—*Tensile properties of materials tested in Table 1 at different temperatures*—Continued

Designation	Specimen No.	Test temperature	Proportional limit	Tensile strength	Elongation in 2 inches	Reduction of area	Brinell hardness No.
		° F.	Lbs./in.[2]	Pbs./in.[2]	Per cent	Per cent	
7990		70	45,000 E. L.[3]	108,000	24.2	43.7	186
		1,500	3,600	30,000	29.0	53.0	
		1,500	3,900				
FS-2, lot A		70	68,000 E. L.[3]	100,000	33.0	52.1	181
	1	990	28,000	83,500	21.5	31.4	
	10	990	28,000	85,500	24.5	35.3	
	2	1,200	9,000	60,000	18.5	37.5	
	6	1,200	11,000	64,000	19.0	34.0	
	8	1,360	5,000	38,000	26.0	50.3	
	7	1,360	6,000	41,500	22.5	49.7	
FS-2, lot B		70	54,000 E. L.[3]	99,500	33.0	47.7	172
	3	990	28,000	83,500	21.5	30.7	
	10	990	26,000	87,000	22.0	34.7	
	5	1,200	8,000	59,500	22.5	37.5	
	9	1,200	9,000	62,300	20.5	37.5	
	2	1,360	4,500	37,500	24.5	49.7	
	7	1,360	6,000	37,500	27.5	54.4	
FS-1, lot A		70	63,000 E. L.[3]	112,500	30.0	36.9	207
	8	990	29,000	98,000	23.5	28.1	
	10	990	30,000	97,000	24.0	27.1	
	9	1,200	9,000	78,500	15.0	21.9	
	2	1,200	14,000	72,500	13.0	21.2	
	4	1,200	12,000	70,000	11.0	18.4	
	3	1,360	6,500	46,500	10.0	16.9	
	1	1,360	5,500	47,500	13.5	24.7	
FS-1, lot B		70	57,500 E. L.[3]	110,000	31.0	51.6	200
	2	990	27,000	95,000	25.0	22.6	
	3	990	27,000	97,000	28.0	29.8	
	7	1,200	9,800	79,000	16.5	21.2	
	8	1,200	12,000	76,000	15.5	21.9	
	9	1,200	--------	66,000	14.0	19.1	
	5	1,360	1,000	48,000	13.0	23.0	
	6	1,360	800	50,500	12.5	20.5	
	11	1,360	--------	46,500	12.5	20.0	
	4	1,360	--------	45,000	12.5	21.2	

[3] Elastic limit determined by The Midvale Co.

2. MICROSTRUCTURE

Any marked decrease in mechanical strength of alloys used continuously at elevated temperatures is usually reflected in the changed microstructure of the material. "Structural stability" at high temperature is of paramount importance in determining the usefulness of materials for such service. The microstructure of each of the alloys before and after testing was determined. In addition, the hardness was determined as a further indication of tempering which might have occurred during the heating The results of the hardness tests are summarized in Table 3 and the structures of the different alloys (except the plain carbon steel) are given in Figures 13 to 18, inclusive. The samples representative of the structure of the short-time test bars before heating were taken from the extreme butt ends of the tension bars (figs. 13, 14, 15, and 16) after the completion of the short-time test. The temperature at the ends of these bars was approximately 500° F. lower than at the gage length of the bars and was assumed to be without effect on the original structure. In the case of Figures 16 and 17, the samples were taken from the butt ends of tension bars which had not been heated above room temperature.

The samples representative of the alloys after heating (figs. 15 to 17) were taken at the center of the gage length of the bar close to the fracture in the case of the short-time tests and from a corresponding position (center of gage length) from the bars used in the flow tests. These latter bars were in the unfractured condition.

TABLE 3.—*Hardness of the alloys used, before and after testing*

Designation of steel	Temperature of test		Type of test	Rockwell hardness				Compare figure and micrograph
				Before test		After test		
	°F.	°C.		B	C	B	C	
10–518, lot A	1,000	540	S [1]	87		90		Fig. 14, *a*, *b*.
10–518, lot B	1,000	540	S	95		90		Fig. 14, *c*, *d*.
EE1455	1,200	650	S		28		26	Fig. 13, *c*, *d*.
EE1456	1,200	650	S		25		25	Fig. 13, *e*, *f*.
EE1454	1,200	650	S	101		99		Fig. 13, *a*, *b*.
E3226, lot A	1,000	540	S		36		35	Fig. 14, *e*, *f*.
E3226, lot B	1,000	540	S		26		26	Fig. 14, *g*, *h*.
HF 1/45, lot A	1,000	540	S		46		46	Fig. 15, *a*, *b*.
HF 1/45, lot B	1,150	620	S		36		33	Fig. 15, *c*, *d*.
HF 1/45, lot B	1,000	540	S		42		31	Fig. 15, *e*, *f*.
8/1317, lot A	1,000	540	S		33		33	Fig. 16, *a*, *b*.
8/1317, lot B	1,000	540	S		29		28	Fig. 16, *c*, *d*.
E2457	1,200	650	S		31		27	Fig. 16, *e*, *f*.
7990	1,500	815	S	98		93		Fig. 16, *g*, *h*.
FS–2, lot A	1,360	738	L [2]	91		83		Fig. 17, *a*, *b*.
	1,360	738	S	95		90		Fig. 17, *c*, *d*.
FS–2, lot B	1,360	738	L	86		79		Fig. 17, *e*, *f*.
	1,360	738	S	93		91		Fig. 17, *g*, *h*.
FS–1, lot A	1,360	738	L	93		85		Fig. 18, *a*, *b*.
	1,360	738	S	97		94		Fig. 18, *c*, *d*.
FS–1, lot B	1,360	738	L	87		85		Fig. 18, *e*, *f*.
	1,360	738	S	91		96		Fig. 18, *g*, *h*.

[1] "S," short-time test. [2] "L," long-time or flow test.

VI. DISCUSSION

The decided advantage of alloy steels over plain carbon steel for withstanding a load at elevated temperatures is very evident from the foregoing results. The proportional limit at elevated temperatures of the carbon steel used was very much lower than that of any of the alloy steels used at the corresponding temperature, and, furthermore, when stressed beyond the proportional limit, the rate at which the stress-strain curve for the alloy steels deviated from a straight line was much less than in the case of the carbon steels.

It is of interest to note in the two lots of chromium-vanadium steel (heat 10–518) which had been heat-treated differently so as to produce a decided difference in their tensile properties, as determined under ordinary conditions, that a marked difference in their tensile properties was maintained at temperatures up to 800° to 1,000° F. (425° to 540° C.). However, at the highest temperature used, 1,200° F. (650° C.), the properties of the two lots were nearly the same nor was there any marked difference in the characteristics with respect to "flow."

The addition of tungsten to a chromium-vanadium steel in amounts of approximately 1.5 per cent raised the proportional limits of the steel at elevated temperatures. No marked improvement, however,

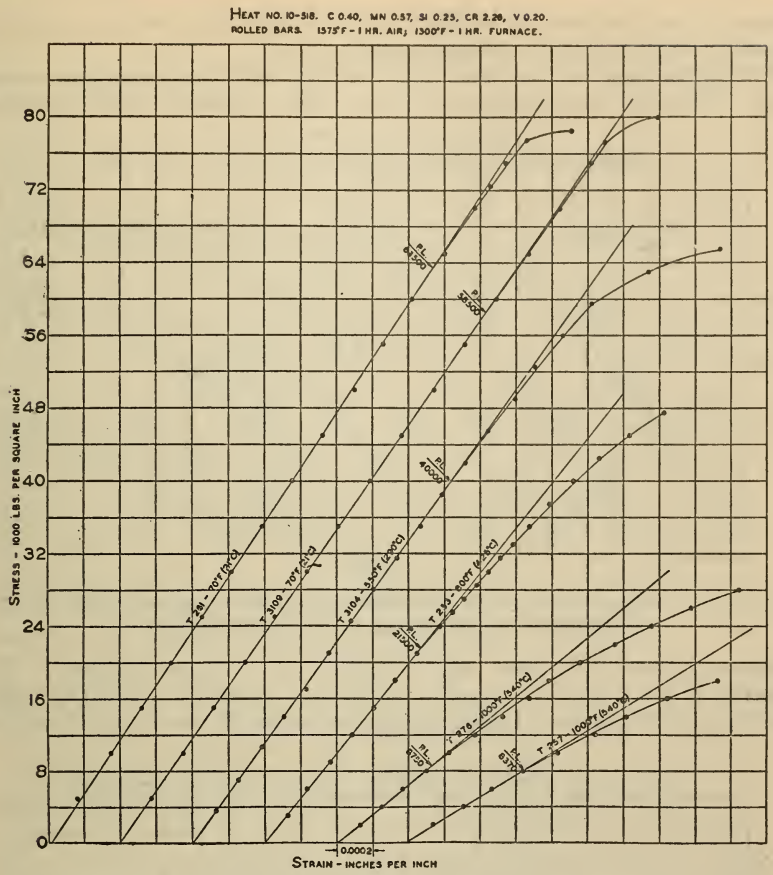
HEAT NO. 10-518. C 0.40, MN 0.57, SI 0.25, CR 2.26, V 0.20.
ROLLED BARS. 1575°F - 1 HR. AIR; 1300°F - 1 HR. FURNACE.
STRESS - 1000 LBS. PER SQUARE INCH
STRAIN - INCHES PER INCH
0.0002
T 68 - 70°F (21°C)
T 3109 - 70°F (21°C)
T 3104 - 300°F (149°C)
T 2345 - 900°F (482°C)
T 270 - 1000°F (540°C)
T 757 - 1600°F (870°C)

FIGURE 2.—*Stress-strain curves of chrominum-vanadium steel tested in tension at different temperatures*

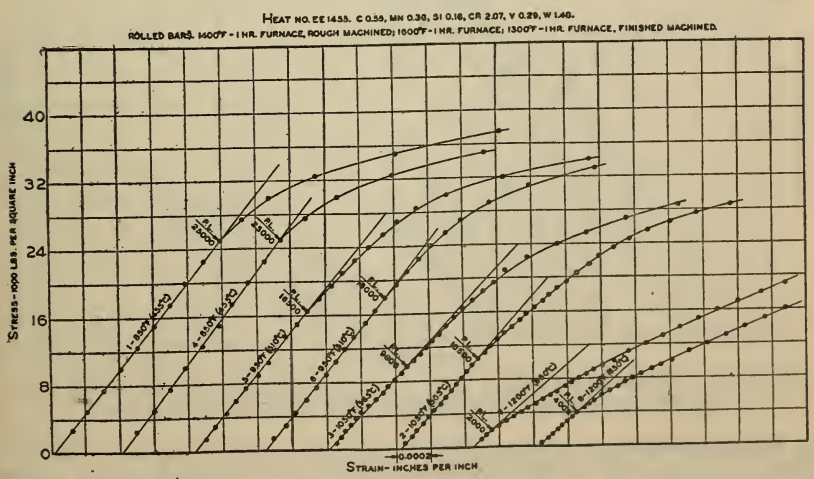
HEAT NO. EE 1453. C 0.59, MN 0.30, SI 0.16, CR 2.07, V 0.29, W 1.40.
ROLLED BARS. 1400°F - 1 HR. FURNACE, ROUGH MACHINED; 1600°F - 1 HR. FURNACE; 1300°F - 1 HR. FURNACE, FINISHED MACHINED.
STRESS - 1000 LBS. PER SQUARE INCH
STRAIN - INCHES PER INCH
0.0002
1 - 350°F (175°C)
4 - 650°F (345°C)
5 - 750°F (400°C)
6 - 850°F (455°C)
3 - 1050°F (565°C)
2 - 1050°F (565°C)
7 - 1200°F (650°C)
8 - 1300°F (705°C)

FIGURE 3.—*Stress-strain curves of chromium-vanadium steel containing tungsten tested in tension at different temperatures*

resulted from the use, in addition to the tungsten, of another alloying element, such as silicon or aluminum.

A comparison of the two lots of the chromium-tungsten steel (heat HF1/45) containing 0.44 per cent carbon, 7.35 per cent

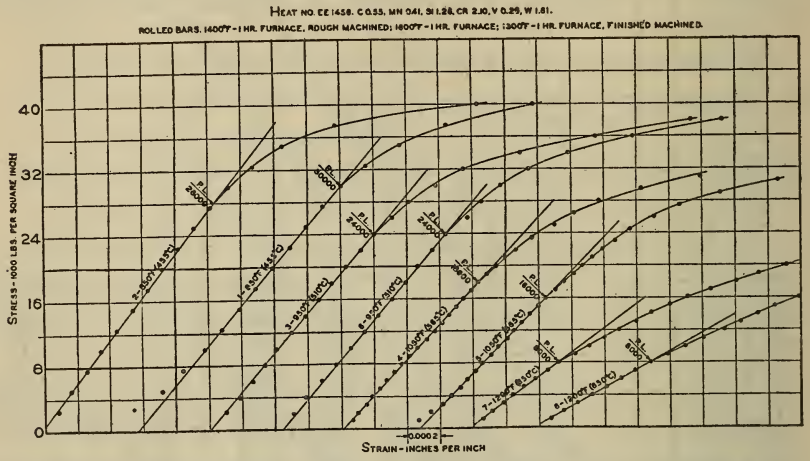
HEAT NO. EE1458. C 0.55, MN 0.41, SI 1.28, CR 2.10, V 0.29, W 1.81.
ROLLED BARS. 1400°F - 1 HR. FURNACE, ROUGH MACHINED; 1800°F - 1 HR. FURNACE; 1300°F - 1 HR. FURNACE, FINISHED MACHINED.
STRESS - 1000 LBS. PER SQUARE INCH
STRAIN - INCHES PER INCH
0.0002
0
8
16
24
32
40

FIGURE 4.—*Stress-strain curves of chromium-vanadium steel containing silicon and tungsten tested in tension at different temperatures*

chromium, and 7.94 per cent tungsten is of some interest. The material of lot A had a proportional limit at 1,000° F. (540° C.) which was about 100 per cent higher than that of lot B due to the fact that

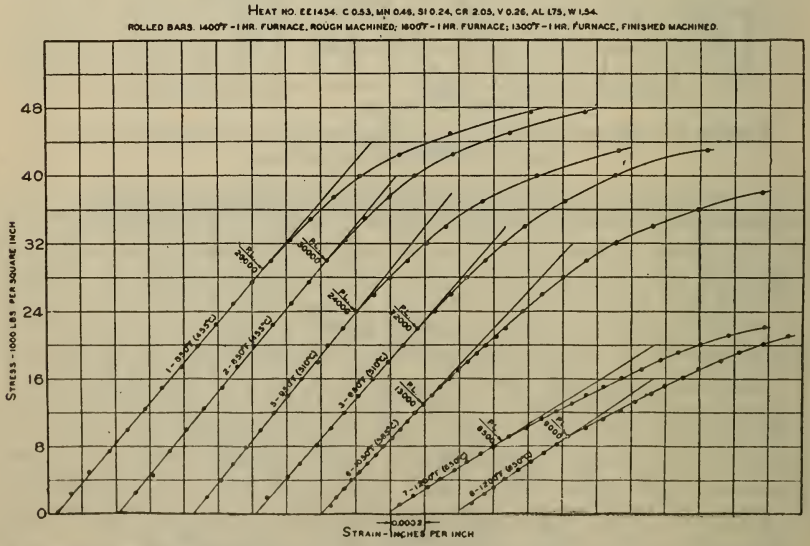
HEAT NO. EE1434. C 0.53, MN 0.46, SI 0.24, CR 2.05, V 0.26, AL 1.75, W 1.54.
ROLLED BARS. 1400°F - 1 HR. FURNACE, ROUGH MACHINED; 1800°F - 1 HR. FURNACE; 1300°F - 1 HR. FURNACE, FINISHED MACHINED.
STRESS - 1000 LBS. PER SQUARE INCH
STRAIN - INCHES PER INCH
0.0003
0
8
16
24
32
40
48

FIGURE 5.—*Stress-strain curves of chromium-vanadium steel containing aluminum and tungsten tested in tension at different temperatures*

the former had been water quenched before tempering at 1,200° F. (650° C.), whereas lot B was normalized before tempering at 1,200° F. Likewise, lots A and B of the nickel-chormium-molybdenum

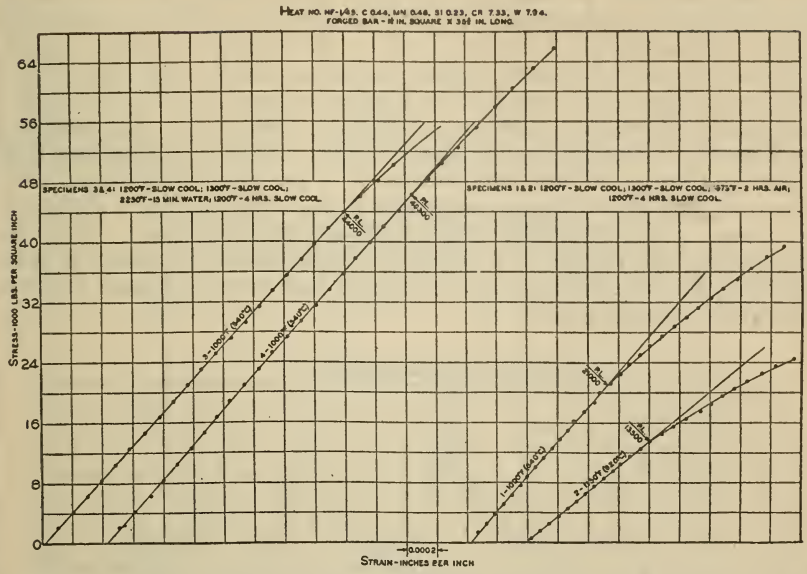
HEAT NO. HF-162. C 0.44, MN 0.46, SI 0.23, CR 7.33, W 7.94.
FORGED BAR - 1" IN. SQUARE X 39" IN. LONG.
SPECIMENS 3 & 4: 1200°F - SLOW COOL; 1300°F - SLOW COOL; 2230°F - 15 MIN. WATER; 1200°F - 4 HRS. SLOW COOL.
SPECIMENS 1 & 2: 1200°F - SLOW COOL; 1300°F - SLOW COOL; 975°F - 2 HRS. AIR; 1200°F - 4 HRS. SLOW COOL.
STRESS - 1000 LBS. PER SQUARE INCH
STRAIN - INCHES PER INCH
0.0002
64
56
48
40
32
24
16
8
0

FIGURE 6.—*Stress-strain curves of chromium-tungsten steel tested in tension at different temperatures*

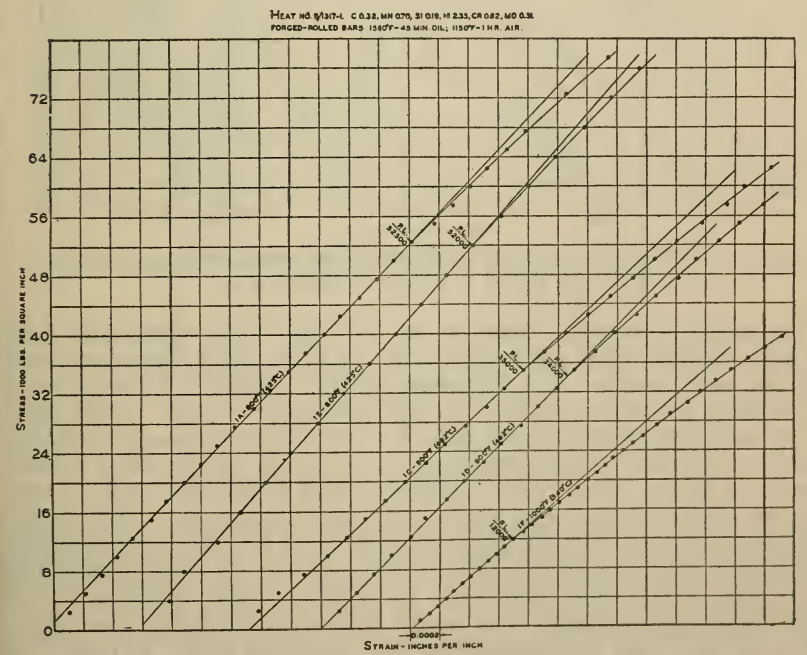

FIGURE 7.—*Stress-strain curves of nickel-chromium steel containing molybdenum tested in tension at different temperatures*

steel (heat 8/1317) containing 0.32 per cent carbon, 2.35 per cent nickel, 0.62 per cent chromium, and 0.31 per cent molybdenum showed different characteristics as determined by the short-time test. Lot A was quenched in oil before tempering while lot B was not. This difference in quenching resulted in higher proportional limits for lot A, especially at temperatures up to 900° F. (480° C.). The properties of the high chromium-nickel steel (heat E–2457) containing 0.39 per cent carbon, 1.50 per cent silicon, 10.5 per cent chromium, 1.61 per cent nickel, and 1.50 per cent aluminum were not very different from those of the nickel-chromium steel just mentioned. This is supported by the results of a previous publication [18] in which it was found that Fe–Cr–Ni alloys low in nickel had low resistance to flow at elevated temperatures.

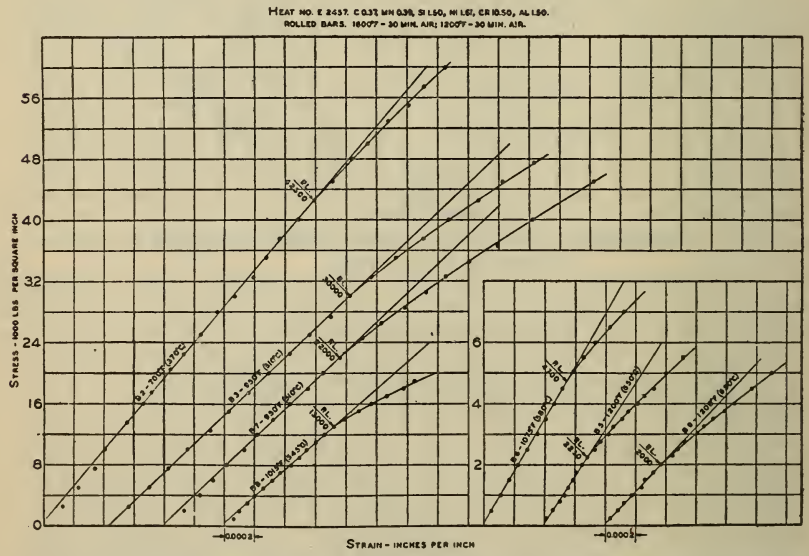
HEAT NO. E 2457. C 0.37, MN 0.39, SI 1.50, NI 1.61, CR 10.50, AL 1.50.
ROLLED BARS. 1800°F - 30 MIN. AIR; 1200°F - 30 MIN. AIR.
STRESS - 1000 LBS. PER SQUARE INCH
STRAIN - INCHES PER INCH
0.0003
0.0005

FIGURE 8.—*Stress-strain curves of nickel-chromium steel containing aluminum tested in tension at different temperatures*

The nickel-chromium-tungsten alloy (heat 7990) containing 0.53 per cent carbon, 26.0 per cent nickel, 14.8 per cent chromium, and 2.93 per cent tungsten was tested at 1,500° F. (820° C.), and showed the highest proportional limit of all the alloys tested. This alloy was quenched in water from 1,835° F. (1,000° C.) and was, therefore, largely austenitic. In this respect it was similar to the other nickel-chromium alloys (heat FS–2) containing 0.28 to 0.32 per cent carbon, 11.12 to 12.93 per cent chromium, and 34.9 to 35.9 per cent nickel, and the nickel-chromium-tungsten alloys (heat FS–1) containing 0.19 to 0.20 per cent carbon, 10.28 to 10.34 per cent chromium, 57.40 to 57.60 per cent nickel, and 3.19 to 3.30 per cent tungsten. The latter alloys gave nearly the same properties in both the short-time and flow tests at temperatures of 1,200° and 1,360° F. (650° and 738° C.). These alloys have a strong tendency to retain austenite

[18] See footnote 2, p. 200.

at both room and elevated temperatures, hence, their properties are not influenced greatly by previous heat treatments, such as annealing or quenching.

In expressing relative merits of steels intended for service at high temperatures, the stress required for causing a total "flow" or extension of 1 per cent or of 0.1 per cent at any given temperatures in 1,000 hours is commonly used. This has been done in Figure 12 which shows

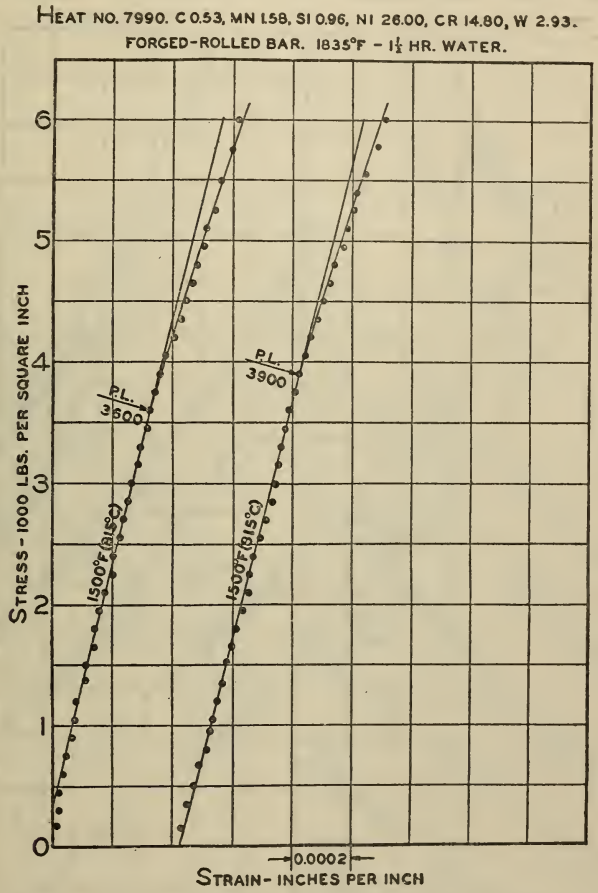

FIGURE 9.—*Stress-strain curves of nickel-chromium-tungsten alloy with high nickel and chromium contents tested in tension at 1,500° F. (815° C.)*

a comparison of the tensile properties, as determined by the short-time tension test and by the flow test, of two general classes of steel at elevated temperatures. The chromium-vanadium steel heat treated in two different ways, has been used as an example of one class, the pearlitic; the steels of high alloy content as representative of the austenitic class.

The question is often asked whether the short-time test can be used to replace the long, tedious, and expensive flow test. It will be noted

(fig. 12) that in the case of the chromium-vanadium steels tested at 550° F. (285° C.), the lowest of the elevated temperatures used, the results indicated good agreement between the proportional limit determined at this temperature and the stress required to produce 0.1 per cent elongation at this same temperature in 1,000 hours. This relationship did not hold at higher temperatures up to 1,200° F., however. The proportional limit determined by the short-time test at any given temperature was considerably higher than the

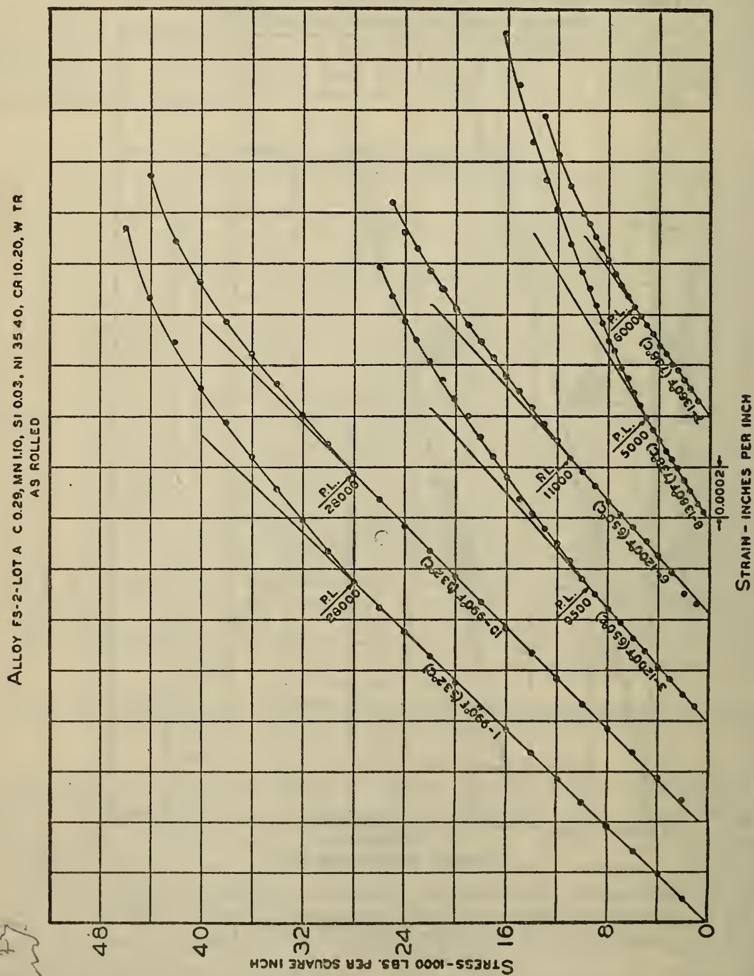

FIGURE 10.—*Stress-strain curves of nickel-chromium-manganese alloy with high nickel and chromium contents tested in tension at different temperatures*

stress required to cause an extension of 1 per cent at that temperature in 1,000 hours. At the highest temperature used, 1,200° F. (650° C.), the stress required for 1 per cent extension in 1,000 hours was only very slightly higher than that required for an extension of 0.1 per cent and neither value differed appreciably from the proportional limit at this temperature.

In the case of the austenitic steels, the agreement between the results of the two tests was even less consistent. For one of the alloys used

(FS–1) the proportional limit at 990° F. (530° C.) determined by the short-time test could be used to indicate, at least approximately, the stress which would result in an extension of 0.1 per cent in 1,000 hours. For the other austenitic alloy at the same temperature, however, conditions were reversed. In this case, the proportional limit indicated the stress which would result in an extension of 1 per cent in 1,000 hours.

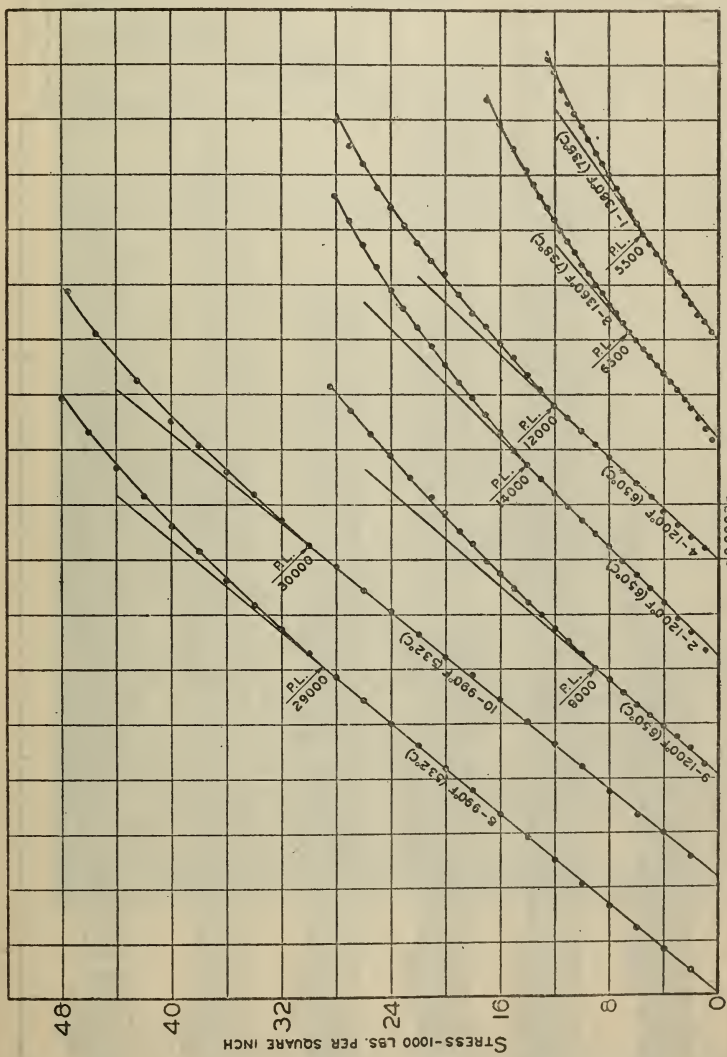

FIGURE 11.—*Stress-strain curves of nickel-chromium-manganese alloy containing tungsten tested in tension at different temperatures*

It is evident from Figures 13, 14, and 15 that there was no noticeable change in the structure caused by the heating during the test period. In these cases, however, the temperature of testing was well below the temperature of the previous tempering treatment given these steels. (Table 1.) In most cases the material after testing was somwhat laminated in structure which may have been

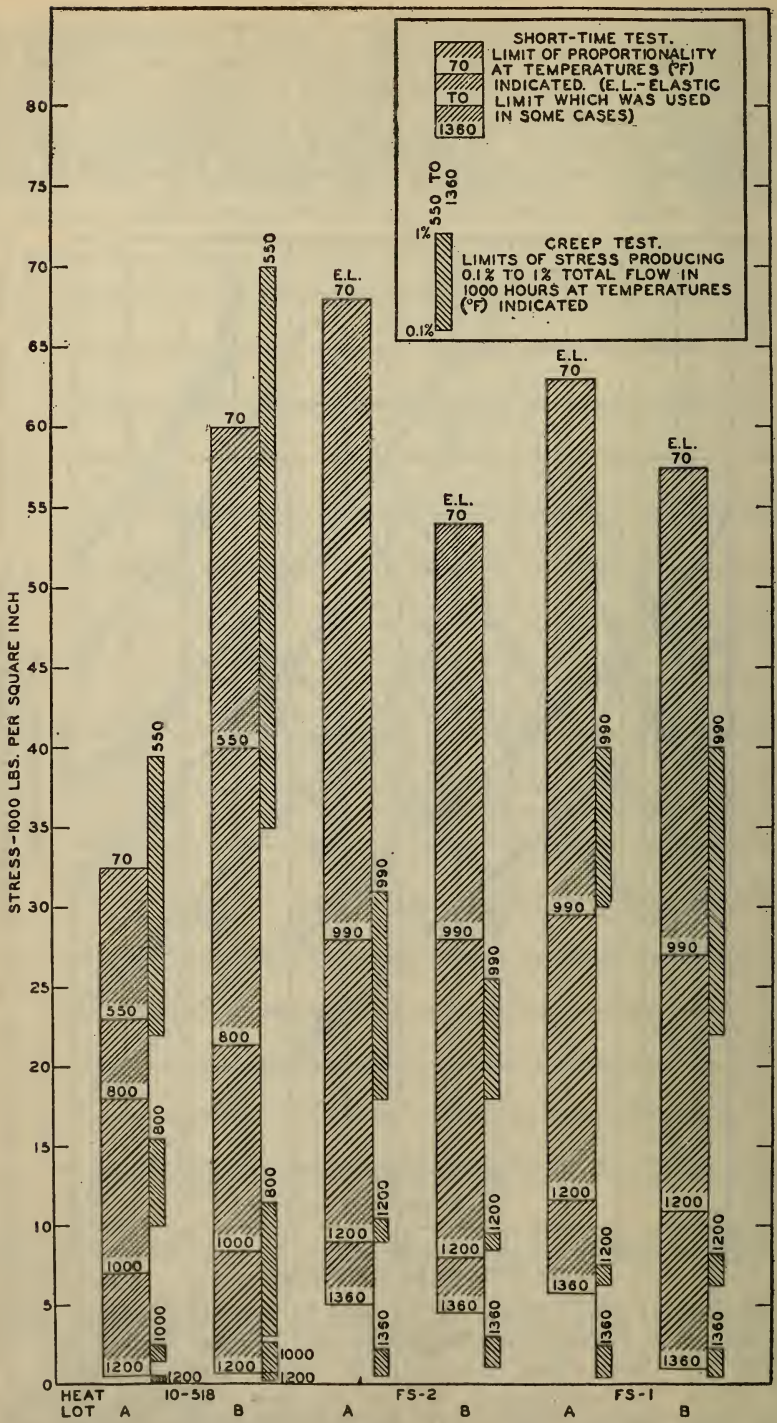

FIGURE 12.—*Comparison of the results of "short-time" and "long-time" or creep tests of steels of the pearlitic and austenitic class*

See Figures 2, 10, and 11.

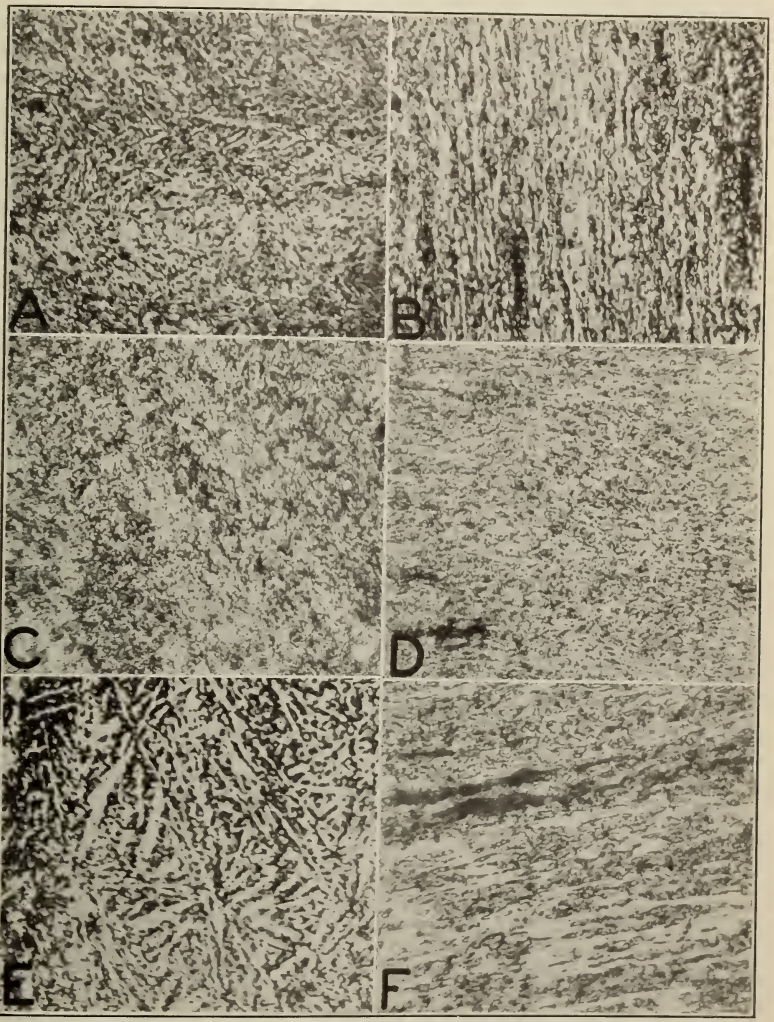

FIGURE 13.—*Structure of chromium-vanadium-tungsten steel before and after testing in tension at 1,200° F. (650° C.) by the "short-time" method.* × 500

A, C, E, initial condition; *B, D, F,* after testing. (See Table 3.) *A, B,* chromium-vanadium-tungsten steel containing aluminum. (Heat EE 1454, Table 1.) *C, D,* chromium-vanadium-tungsten steel containing silicon. (Heat EE 1455, Table 1.) *E, F,* chromium-vanadium-tungsten steel. (Heat EE 1456, Table 1.) The etching reagent used on the specimens shown here and in succeeding figures was aqua regia in glycerin.

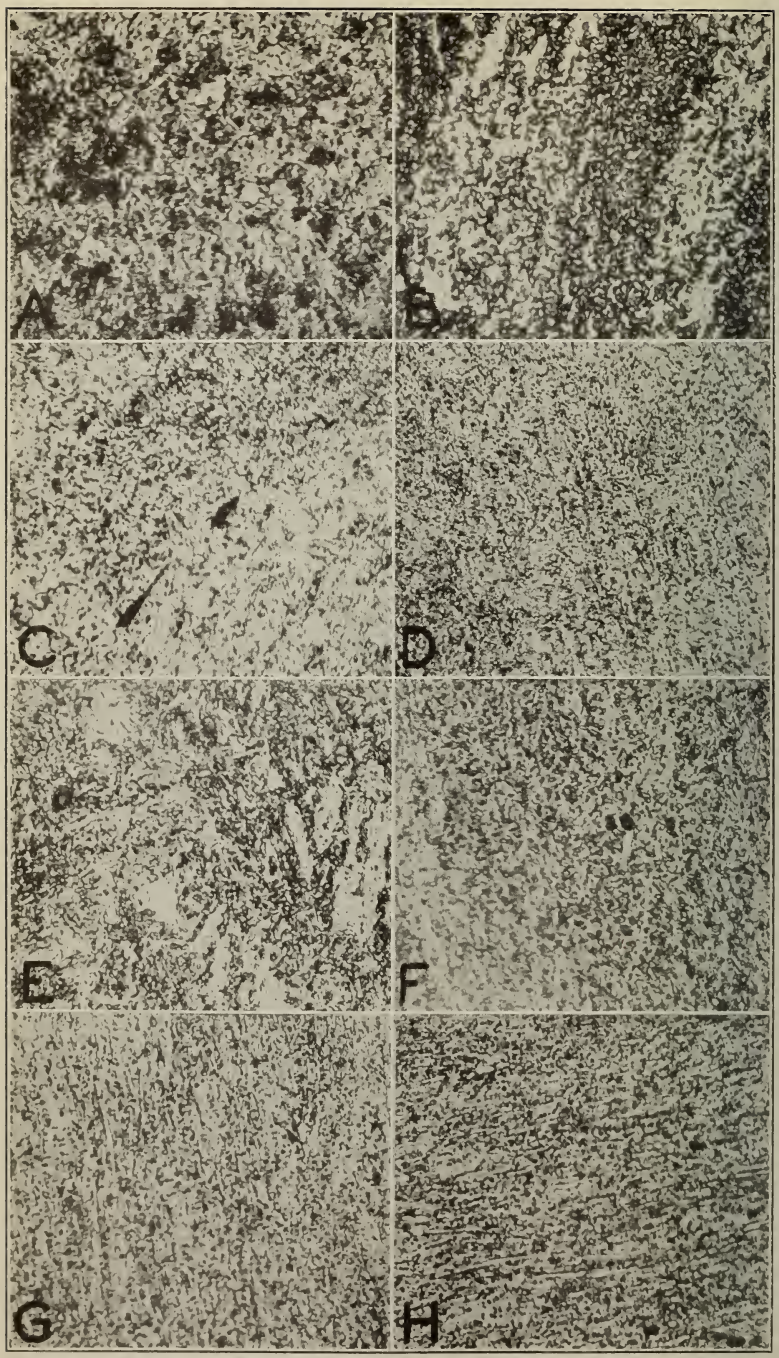

FIGURE 14.—*Structure of chromium-vanadium steel and of chromium-vanadium-tungsten steel before and after testing in tension at 1,000° F. (540° C.) by the "short-time" method.* × *500*

A, C, E, G, initial condition; *B, D, F, H,* after testing. (See Table 3.) *A, B, C, D,* chromium-vanadium steel. (Heat 10–518, lots A and B, Table 1.) *E, F, G, H,* chromium-vanadium-tungsten steel. (Heat E 3226, lots A and B, Table 1.)

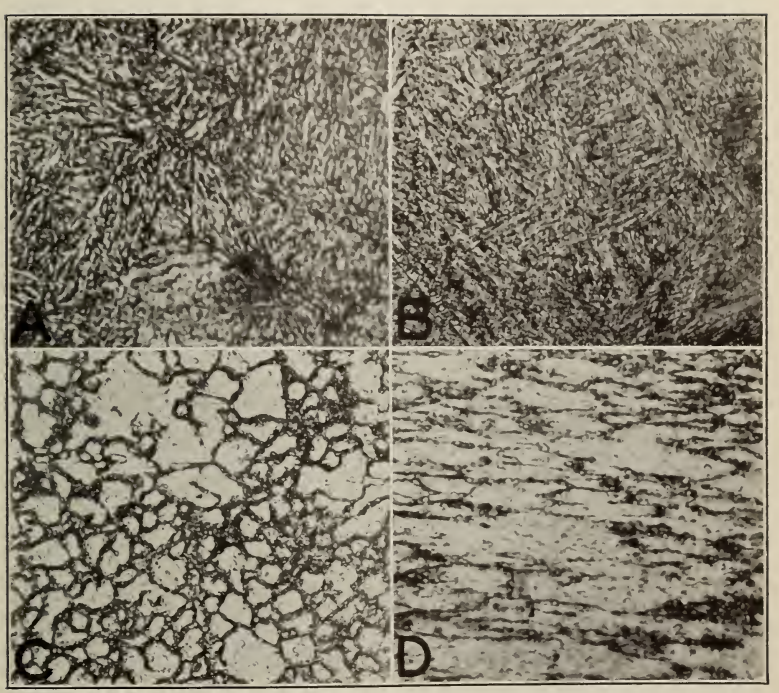

FIGURE 15.—*Structure of chromium-tungsten steel (heat IIF 1–45, lots A and B, Table 1) before and after testing in tension at 1,000° F. (540° C.) by the "short-time" method.* × *500*

A, C, initial condition; *B, D,* after testing. (See Table 3.)

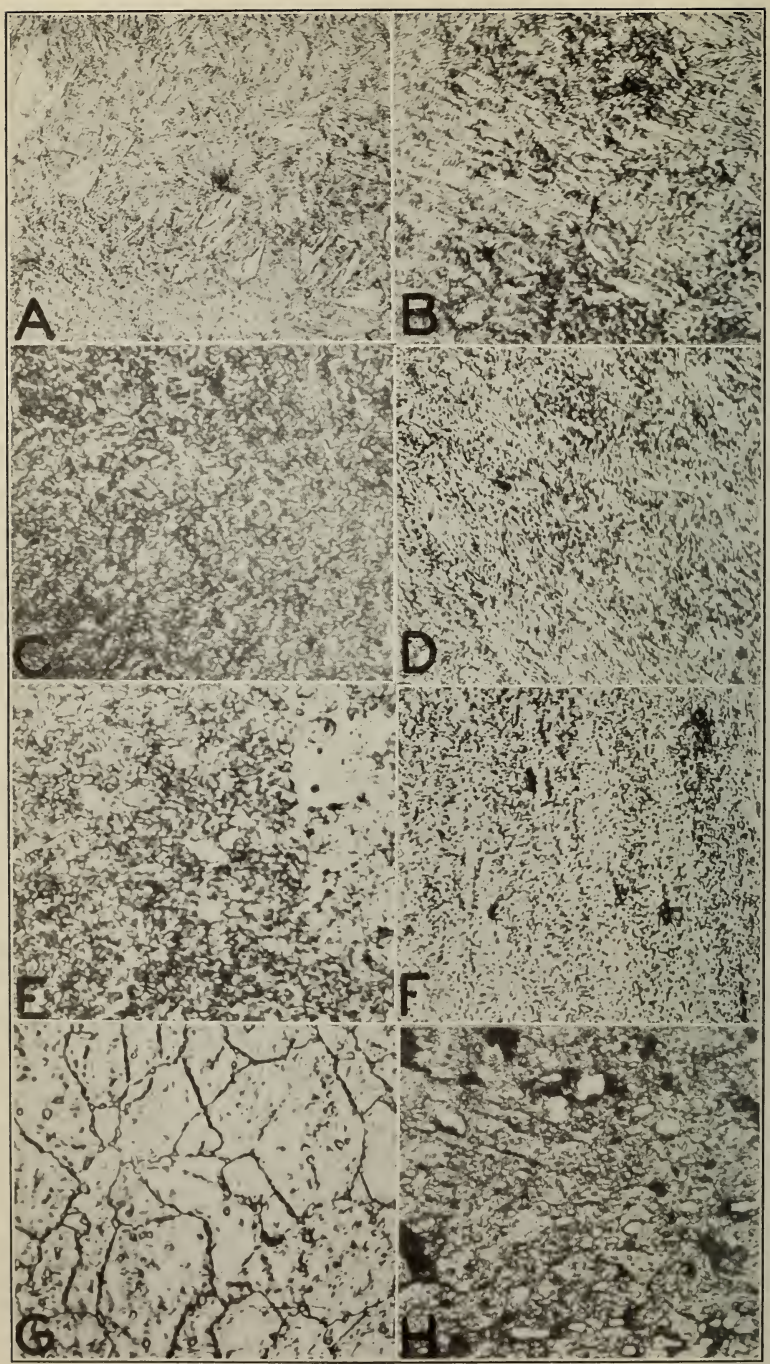

FIGURE 16.—*Structure of various alloy steels before and after testing in tension at elevated temperatures by the "short-time" test.* × *500*

A, C, E, G, initial condition; *B, D, F, H,* after testing. (See Table 3.) *A, B, C, D,* nickel-molybdenum steel (heat 8-1317, lots A and B, Table 1) tested at 1,000° F. (540° C.). *E, F,* chromium-nickel steel containing aluminum (heat 2457, Table 1) tested at 1,200° F. (650° C.). *G, H,* chromium-nickel-tungsten steel (heat 7990, Table 1) tested at 1,500° F. (815° C.)

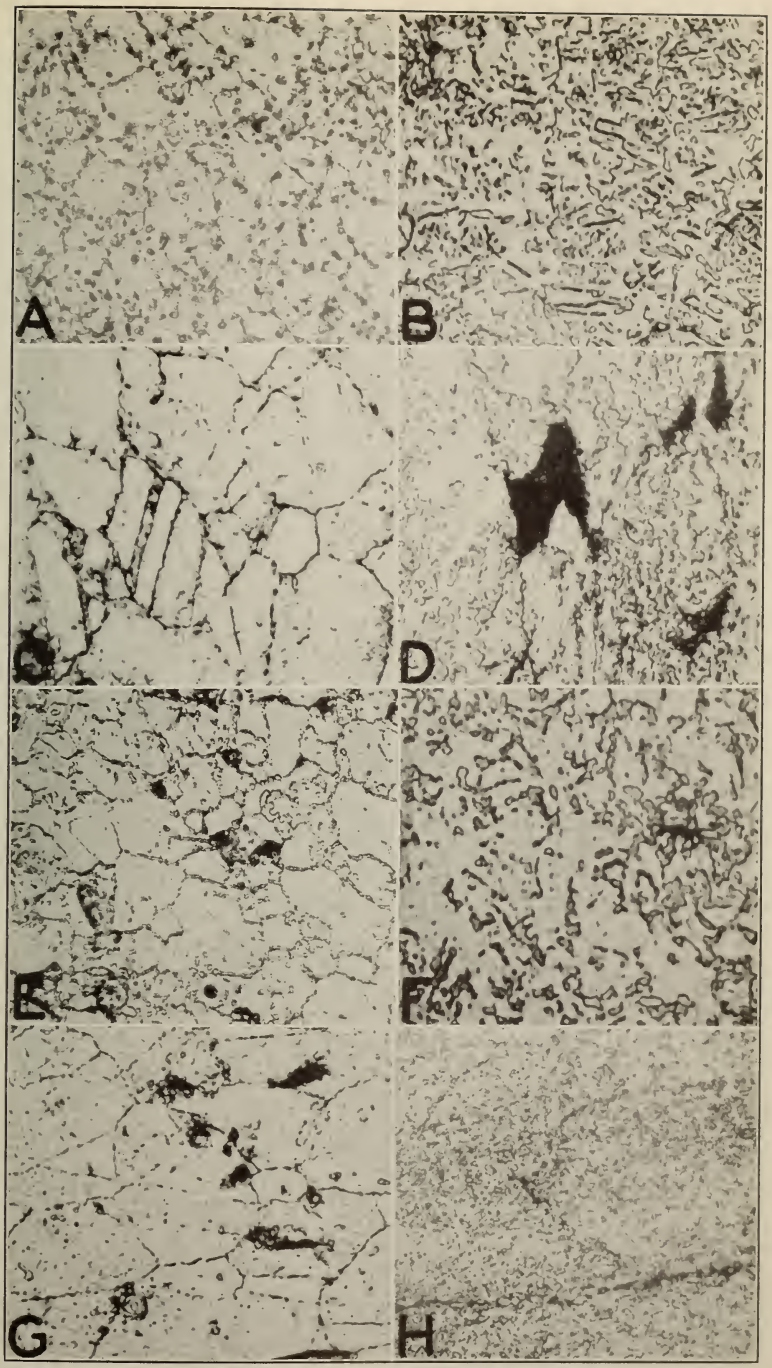

FIGURE 17.—*Structure of chromium-nickel alloy (heat FS–2, lots A and B, Table 1) before and after testing in tension at 1,360° F. (735° C.). × 500*

A, C, E, G, initial condition; *B, D, F, H,* after testing. (See Table 3.) *B,* after "long-time" or creep test; 335 hours, load 4,100 lbs./in.², total extension 0.56 per cent. *D,* after short-time test. *F,* after creep test; 335 hours, load 4,100 lbs./in.², total extension 0.80 per cent. *H,* after short-time test.

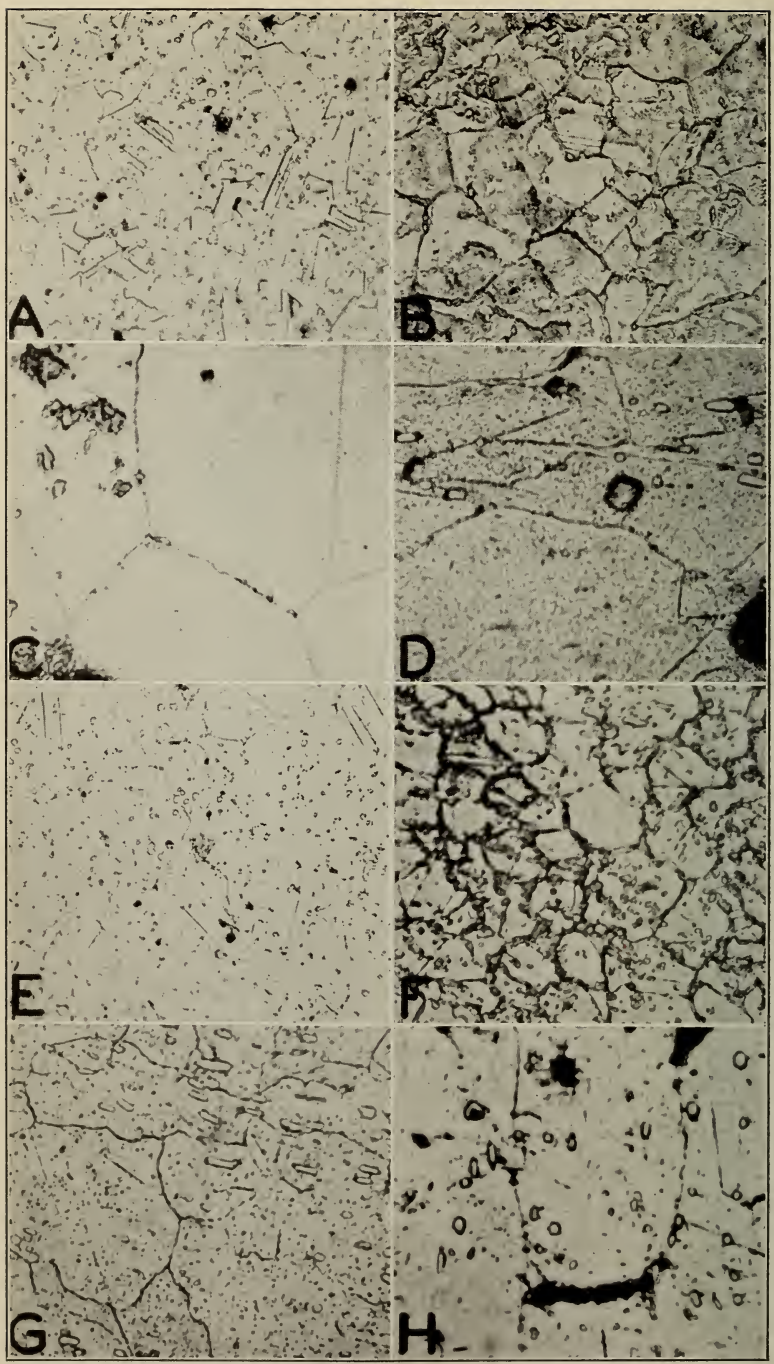

FIGURE 18.—*Structure of chromium-nickel-tungsten alloy (heat FS–1, lots A and B, Table 1), before and after testing in tension at 1,360° F. (735° C.). × 500*

A, C, E, G, initial condition; *B, D, F, H,* after testing. (See Table 3.) *B,* after "long-time" or creep test; 405 hours with load of 2,400 lbs./in.², then 147 hours with 8,500 lbs./in.², total elongation 2.6 per cent. *D,* after "short-time" test. *F,* after creep test, 405 hours with load of 2,500 lbs./in.², then 147 hours with 8,500 lbs./in.², total elongation, 3.4 per cent. *H,* after sohrt-time test.

on account of the fact that the alloys were strained below their lower transformation temperature. This might be expected to increase the hardness somewhat, but it was found that in most of the materials represented by Figures 13, 14, and 15 there was a slight decrease in hardness after testing.

The medium alloy steels designated as 10–518, EE1455, EE1456, and 8/1317 appeared to be mostly sorbitic in structure (figs. 13, 14, and 15) while the high chromium-tungsten steel, HF–1/45, contained grains of sorbite with a network of troostite and some carbide constituent.

The high chromium steel E2457 (fig. 16), showed slight agglomeration of the cementitic constituent during the heating incidental to testing and the high nickel-chromium steel, 7990 (fig. 16), did likewise.

It is interesting to note that the nickel-chromium steel (FS-2) containing about 35 per cent nickel, 12 per cent chromium and 0.30 per cent carbon showed considerable agglomeration of the carbide constituent occurred (fig. 17) during both the "short-time" and the "long-time" tests. Before testing, these steels were essentially austenitic with small isolated particles of the carbide constituent. After testing these alloys at 1,360° F. (735° C.), it was found that the lots in the "as rolled" state, and in the "rolled and annealed at 1,650° F. (900° C.)" state, showed considerable precipitation and agglomeration of the carbide constituent.

In the case of the higher nickel-chromium steel (FS–1) (fig. 18) containing about 57 per cent nickel, 10 per cent chromium, 3.25 per cent tungsten, and 0.20 per cent carbon, there appeared to be no marked change in structure with respect to the condition of the carbide constituent after similar treatments. It must be remembered that this alloy contains about 0.10 per cent less carbon than FS–2, but it is believed that the additional 22 per cent nickel, together with about 3.20 per cent tungsten is more likely to account for its increased stability as regards tempering.

VII. SUMMARY

1. The tensile properties of a number of steels at a series of different elevated temperatures have been determined by means of the "short-time" test. The proportional limit was determined in each case. The steels used were a plain carbon steel, such as is used in boiler drums, and a number of alloy steels which have been considered in industry for service at high temperatures. The following were included: chromium-vanadium, chromium-vanadium-tungsten (the latter also with additions of silicon or aluminum) chromium-tungsten, nickel-moybdenum, and several austenitic steels containing nickel and chromium and, in some cases, tungsten.

2. The addition of tungsten, in amounts of 1.5 to 2 per cent, to a chromium-vanadium steel improves the tensile properties at high temperatures very decidedly. The further addition of silicon or aluminum does not appear to result in any marked improvement.

3. According to the short-time tests a marked increase in tensile properties of a steel brought about by heat treatment is maintained at elevated temperatures only so long as the temperature of testing

is kept well below that used in tempering the steel in the preliminary heat treatment.

4. Both "short-time" tests and "flow" tests were carried out on several of the steels representative of the two classes—pearlitic and austenitic. According to the results, the "short-time" test can not satisfactorily replace the "flow" test in the evaluation of steels for service involving loads at high temperatures.

VIII. ACKNOWLEDGMENTS

The authors wish to express their appreciation to S. J. Rosenberg, associate metallurgist, and to S. E. Sinclair, junior metallurgist, of this bureau, for help in preparing many of the figures and micrographs.

Washington, October 15, 1930.

7/13/54

PLEASE RETURN 1 WEEK FROM DATE OF RECEIPT BY REGISTERED MAIL OR INSURED PARCEL POST. PERIODICALS CANNOT BE RENEWED. THE PACKAGE SHOULD BE ADDRESSED:

NATIONAL BUREAU OF STANDARDS LIBRARY
ROOM 301 NORTHWEST BUILDING
CONNECTICUT AVENUE & VAN NESS STREET
WASHINGTON 25, D. C.

SARAH ANN JONES
LIBRARIAN